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Enantioselective Strecker-type reaction of phosphinoyl ketimines catalyzed by a chiral Zr-bipyridyldiol catalyst

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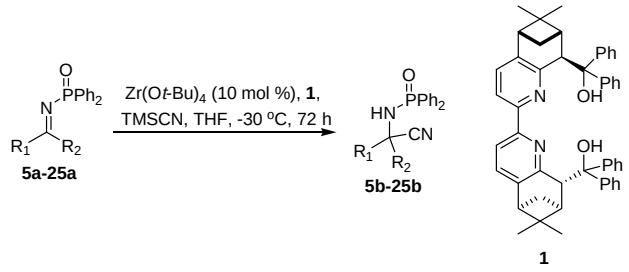
ABSTRACT

An enantioselective Strecker reaction of *N*-diphenylphosphinoyl ketimines with TMSCN employing a chiral zirconium complex formed from chiral bipyridyl diol **1** as catalyst is described. The catalytic efficiency of chiral ligand **1** with other Lewis acids was also explored. Higher yields (50–85%) with moderate to good enantioselectivities (30–80%) were achieved for a variety of *N*-diphenylphosphinoyl ketimines.

1. Introduction

Chiral cyanohydrins are highly versatile intermediates, which can be converted into a wide range of pharmaceutically and industrially useful chiral compounds. The catalytic asymmetric Strecker reaction[1] is one of the most convenient methods for the synthesis of chiral amino nitriles in high yields.[2] The process involves the addition of trimethylsilyl cyanide (TMSCN) or HCN to aldimines in the presence of a chiral catalyst. A variety of C_1 or C_2 symmetric chiral diamides, TADDOLs, BINOL, salen and other ligands in combination with Lewis acids such as Ti(O*i*-Pr)$_4$, $TiCl_4$, $AlCl_3$, Gd(O*i*-Pr)$_3$, Et_2AlCl and Zr(O*t*-Bu)$_4$ were reported to induce high enantioselectivity during the reaction.[3] Lipton et al. investigated the viability of the asymmetric Strecker synthesis of amino acids using a cyclic guanidine dipeptide in the reaction of *N*-benzhydrylimines with hydrogen cyanide to *N*-benzhydryl-α-aminonitriles.[4] Jacobsen et al. reported chiral 1,2-*trans*-diaminocyclohexanes modified with urea and thiourea functionalities on one side, and salicylaldimine on the other side[5,6] to furnish efficient organocatalysts for the cyanohydrination of imines. Although asymmetric hydrocyanation of aldimines has been well established with high yields and enantioselectivity, the more related reaction of ketimines has not been fully explored. Recently, more enantioselective catalysts have been applied to improve the asymmetric induction of Strecker reaction involving ketimines as substrates.[7] Among the ketimines activated with different protections at the imine, *N*-diphenylphosphinoyl ketimines are reported to be better substrates for the Strecker reaction which require protic additives in the reaction.[8] Chiral alkyl diphenylphosphinite in combination with two hydroxyl groups and Gd(O*i*-Pr)$_3$[9] and chiral bifunctional *N*,*N*′-dioxides derived from L-prolinamide[10] were the two catalyst systems reported to induce high enantioselectivity in the asymmetric Strecker reaction of ketimines. The use of structurally different chiral ligands is therefore essential for a broad substrate scope and in the improvement of the enantioselectivity of ketimine substrates.

As an extension of our earlier work on the asymmetric addition of TMSCN to aldehydes forming chiral cyanohydrins in good enantiomeric excess using chiral Ti-**1** catalyst,[11a] chiral ligand **1** with different Lewis acids was explored towards the enantioselective addition of TMSCN to *N*-diphenylphosphinoyl ketimines (Scheme 1).



Scheme 1. Enantioselective Strecker reaction of *N*-diphenylphosphinoyl ketimines catalyzed by Zr(O*t*-Bu)$_4$-**1**.

2. Results and discussion

As an initial effort towards the ligand synthesis, chiral *N*,*N*-dioxide **4** resembling Feng's catalyst[10] was synthesized from chiral bipyridine **2**[11c] according to Scheme 2. Treatment of **2** with LDA, followed by reaction with diphenylphosphinoyl chloride afforded bipyridine **3** in 64% yield. Oxidation of **3** with *m*CPBA formed the chiral *N*,*N*-dioxide **4** in excellent yield.

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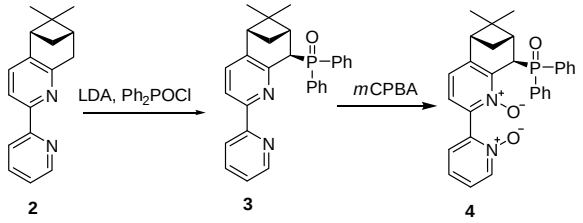
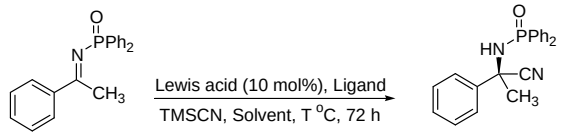


Scheme 2. Synthesis of the chiral ligands **3** and **4**.

Chiral bipyridyldiol **1** was synthesized following the reported protocol.[11b] The chiral ligands **1**, **3** and **4** were screened for the asymmetric addition of TMSCN to *N*-diphenylphosphinoyl ketimines following the protocol reported in the literature (Scheme 1). Accordingly the ligands were treated with an equal amount of Zr(O*t*-Bu)$_4$ (10 mol %) and the in situ formed catalysts were used for the addition of TMSCN to *N*,*N*-diphenyl-*N*-(1-phenylethylidene)phosphinamide **5a** at −40 °C. After considerably longer reaction times (40 h), the Strecker product **5b** (Table 1) was formed in excellent yield, however, no chiral induction was observed with either of the ligands **3** and **4** (Table 1, entries 1 and 2). Interestingly, there was no reaction when ligand **4** was used in the absence of any Lewis acid (Table 1, entry 3). On the other hand, ligand **1** under identical reaction conditions afforded the (*S*)-enantiomer in 20% enantiomeric excess and 73% isolated yield (Table 1, entry 4). Based on this preliminary observation, ligand **1** was used for further exploration of the reaction. A variety of reaction conditions (temperature, reaction time and catalyst loading) and Lewis acids were attempted to establish the optimized reaction condition. Alternatively, the Strecker reaction of other activated ketimine substrates with benzyl and benzhydryl protection at the imine were subjected to reaction with TMSCN in the presence of the zirconium catalyst (formed from **1**, **3** and **4**). All the catalysts employed afforded the corresponding Strecker product in good yields but in poor enantioselectivities under different reaction conditions.

Table 1
Asymmetric Strecker reaction of **5a** catalyzed by various Lewis acid–ligand complexes in different solvents



5a **5b**

Entry	Ligand 10 mol %	Lewis acid	Solvent	*T* (°C)	Conversion[a,b] (%)	ee[c] (%)
1	**3**	Zr(O*t*-Bu)$_4$	Toluene	−40	85	2
2	**4**	Zr(O*t*-Bu)$_4$	Toluene	−40	97	0
3	**4**	None	Toluene	−40	—	—
4	**1**	Zr(O*t*-Bu)$_4$	Toluene	−40	73	20
5	**1**	Ti(O*i*-Pr)$_4$	Toluene	−40	72	0
6	**1**	Et$_2$AlCl	Toluene	−40	65	0
7	**1**	Gd(O*i*-Pr)$_3$	Toluene	−40	95	3
8	**1**	Zr(O*t*-Bu)$_4$	Toluene	rt	90	2
9	**1**	Zr(O*t*-Bu)$_4$	THF	rt	95	17
10	**1**	Zr(O*t*-Bu)$_4$	CH_2Cl_2	rt	96	4
11	**1**	Gd(O*i*-Pr)$_3$	Toluene	rt	92	0
12	**1**	Gd(O*i*-Pr)$_3$	THF	rt	90	3
13	**1**	Gd(O*i*-Pr)$_3$	CH_2Cl_2	rt	93	2

[a] Conversions were determined by chiral HPLC.
[b] *t* = 40 h.
[c] Determined by HPLC on chiral OD column and the absolute configuration was assigned (*S*) based on comparison with the literature data.[7]

2.1. Effect of reaction solvents and Lewis acids on the enantioselective addition of TMSCN to *N*-diphenylphosphinoyl ketimines

The asymmetric addition of TMSCN to **5a** was screened with catalytic species formed from chiral ligand **1** and different Lewis acids (Table 1). Accordingly four different Lewis acids (10 mol %), namely Ti(O*i*-Pr)$_4$, Et$_2$AlCl, Gd(O*i*-Pr)$_3$ and Zr(O*t*-Bu)$_4$, were employed for the reactions performed at −40 °C in toluene. The most commonly employed titanium complex afforded only the racemic **5b** (72%) even after longer reaction times (Table 1, entry 5). In a similar way, no enantioselectivity was observed in the case of Et$_2$AlCl (65% of racemic **5b**). The lanthanide metal complex Gd(O*i*-Pr)$_3$, however, gave promising results, although with poor enantioselectivity (95% yield; 3% ee). The reactions involving lanthanide complexes Gd(O*i*-Pr)$_3$-**1** and Zr(O*t*-Bu)$_4$-**1** were then performed in solvents other than toluene (Table 1, entries 9–13) to improve the enantioselectivity of the reaction. Tetrahydrofuran was found to be better solvent for the Zr(O*t*-Bu)$_4$-**1** catalyzed reaction displaying higher selectivity (Table 1, entry 9). Gd(O*i*-Pr)$_3$-**1**, did not exhibit any improvement in the enantioselectivity of the reaction under the conditions screened and therefore was not explored further.

2.2. Effect of reaction temperature and catalyst loading on the enantioselective addition of TMSCN to *N*-diphenylphosphinoyl ketimines

The asymmetric addition of TMSCN to ketimine **5a** was then performed with different catalyst loadings of Zr(O*t*-Bu)$_4$-**1** (1−20 mol %) and at different reaction temperatures in THF (Table 2).

Table 2
Effect of the reaction temperature and catalyst loading on the asymmetric Strecker reaction of **5a**

Entry	Catalyst loading (mol %)	*T* (°C)	Conversion[a,b] (%)	ee[c] (%)
1	10	0	93	37
2	10	−20	84	74
3	10	−40	33	78
4	1	−20	—	—
5	5	−20	30	54
6	20	−20	98	63

[a,b,c] See Table 1.

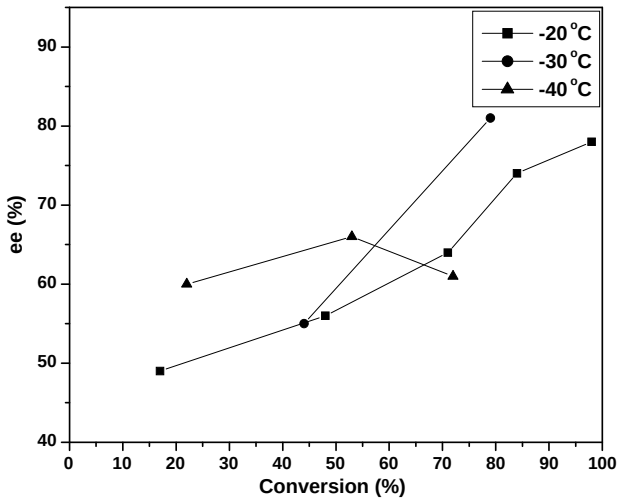
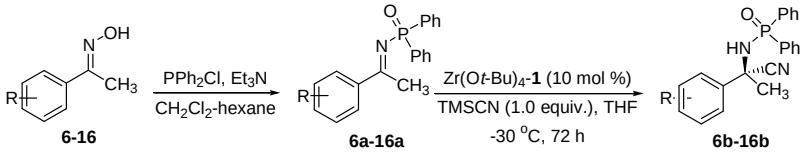


Figure 1. Conversion and enantiomeric excess of **5a** at different temperatures.

Table 3
Results of the effect of aryl substituents on the asymmetric Strecker reaction of ketimines



Entry	Substrate	Product	Yield[a] (%)	ee[b] (%)	$[\alpha]_D$ (*c* CH_2Cl_2)
1	**6a**; R = *o*-OMe	**6b**	81	64 (*S*)	−2.15 (1.3)
2	**7a**; R = *m*-OMe	**7b**	86	72 (*S*)	−4.9 (1.6)
3	**8a**; R = *p*-OMe	**8b**	63	34 (*S*)	−2.35 (0.85)
4	**9a**; R = *o*-Me	**9b**	87	36 (*S*)	−2.7 (2.0)
5	**10a**; R = *m*-Me	**10b**	76	68 (*S*)	−1.7 (1.05)
6	**11a**; R = *p*-Me	**11b**	63	70 (*S*)[d]	−4.8 (0.9)
7	**12a**; R = *o*-Br	**12b**	52	—[c]	−1.3 (1.15)
8	**13a**; R = *m*-Br	**13b**	67	54 (*S*)	−4.6 (1.4)
9	**14a**; R = *p*-Br	**14b**	85	44 (*S*)	−6.4 (1.15)
10	**15a**; R = *m*-Cl	**15b**	78	46 (*S*)	−3.2 (1.25)
11	**16a**; R = *p*-Cl	**16b**	76	60 (*S*)[d]	−5.7 (0.85)

[a] Isolated yield of α-aminonitriles.
[b] Determined by HPLC on chiral OD column and the absolute configurations were assigned based on comparison with the literature data.
[c] Ee could not be determined by HPLC.
[d] Please see Ref. 9.

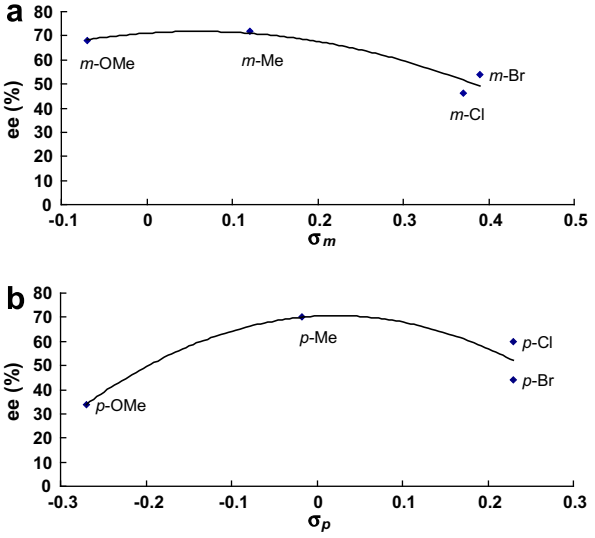


Figure 2. The plots of the enantiomeric excess of the reaction and Hammett substituent constants [σ_m (a) and σ_p (b)].

Lower temperatures improved the enantioselectivity of the reaction drastically although the reactions were comparatively slower and required longer reaction times for higher conversions. In a similar manner, an increase in catalyst loading at lower temperature improved both the yields and enantiomeric excess of **5b**. The optimum catalyst loading was found to be 10 mol % (Table 2, entry 2), beyond which the enantioselectivity of the catalyst deteriorated (Table 2, entry 6).

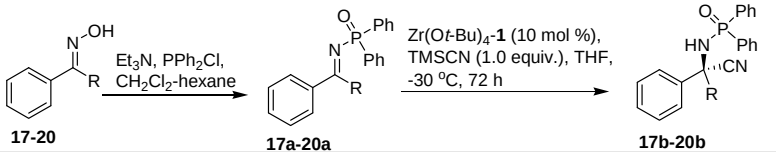
An increase in the reaction time generally afforded higher conversions and better enantioselectivity as seen in Figure 1. The reaction of **5a** using 10 mol % of Zr-**1** was studied at three different temperatures in different time intervals. At temperatures beyond −30 °C, slower reaction rates with moderate enantioselection were observed. The optimum reaction temperature was hence assigned as −30 °C (72 h), which afforded the highest enantioselectivity compared to the equally efficient −20 °C.

2.3. Effect of substrate structure

The catalytic efficiency of Zr(O*t*-Bu)$_4$-**1** towards the asymmetric Strecker reaction of different ketimines was investigated under the optimized reaction condition.

A series of *N*-diphenylphosphinoyl ketimines **6a**–**16a** were synthesized from various acetophenone oximes **6**–**16** and subjected to a Strecker reaction in order to study the electronic influence of substituents on the aryl moiety on the enantioselectivity of the reaction. The isolated yields and enantiomeric excess of asymmetric Strecker reaction of ketimines **6a**–**16a** by Zr(O*t*-Bu)$_4$-**1** is shown in Table 3.

Table 4
Asymmetric Strecker reaction of phenylalkyl ketimines with TMSCN



Substrate	Product	Yield[a] (%)	ee[b] (%)	$[\alpha]_D$ (*c* CH_2Cl_2)
17a; R = Et	**17b**	68	10	+0.9 (1.2)
18a; R = ^{n}Pr	**18b**	68	42	−3.4 (0.85)
19a; R = ^{i}Pr	**19b**	73	35	−3.2 (1.05)
20a; R = H	**20b**	75	10	−0.6 (1.2)

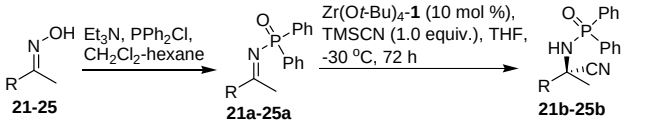
[a,b] See Table 3.

Ketimines with electron rich methoxy and methyl groups (at the *meta*-position) afforded higher enantiomeric excesses compared to electron deficient halogens. The substituents at the *meta*-position of the aryl moiety showed higher enantioselectivities when compared to the same substituent on the other positions. The plots of the enantiomeric excess of the reaction and Hammett substituent constants (σ_m and σ_p) (Fig. 2a and b) are interesting and showed the apparent substituent effect of the substrates on the enantioselectivity of the reaction. Electron-withdrawing groups and mild electron releasing groups at the *para*-positions of the aryl moiety of the ketimines displayed higher ee in comparison to the strongly electron releasing groups at the same position (Fig. 2b). In general, the substituent effect of the substrates in these reactions differs markedly to that observed in the asymmetric TMSCN addition to aldehydes by the same chiral ligand **1**.[11a]

The influence of the alkyl part of the substrate on the enantioselectivity of the reaction was studied with ketimines possessing alkyl groups **17a**–**19a** larger than a methyl group. The ketimine substrates were synthesized from the corresponding phenyl alkyl ketoximes **17**–**19** and reacted with TMSCN in the presence of Zr-**1** as described earlier (Table 4). Under identical reaction conditions, the yield and enantiomeric excess in the case of these substrates were lower than **5a** which could probably be as a result of increase in steric crowding. The benzaldoxime derived *N*-diphenylphosphinoyl aldimine **20a**, however, formed the Strecker product **20b** in low enantiomeric excess though in good yield (Table 4, entry 4).

The efficiency of the new catalyst system was then explored with ketimines **21a**–**25a** possessing different aryl or heteroaromatic ring. Though a good yield of Strecker product was obtained in all the cases (Table 5), the enantioselectivities were moderate to low under the reaction condition employed. As expected, ketimine **23a** with a furanyl moiety underwent the Strecker reaction with high enantioselectivity forming **23b** in 76% ee as a result of the oxophilic nature of the zirconium catalyst (Table 5, entry 3).[9]

Table 5
Substrate generality of the asymmetric Strecker reaction of ketimines



Entry	Substrate	Product	Yield[a] (%)	ee[b] (%)	$[\alpha]_D$ (*c* CH_2Cl_2)
1	**21a**; R = 1-naphthalenyl	**21b**	73	—[c]	−1.2 (1.25)
2	**22a**; R = 2-naphthalenyl	**22b**	79	10	−0.3 (1.9)
3	**23a**; R = 2-furanyl	**23b**	58	76	−2.7 (0.9)
4	**24a**; R = 3-thiophenyl	**24b**	65	3	−0.9 (1.05)
5	**25a**; R = 3-pyridinyl	**25 b**	67	24	−2.4 (1.05)

[a] Isolated yield of α-aminonitriles.
[b] Determined by HPLC on chiral OD column and the absolute configurations were assigned based on comparison with the literature.
[c] Ee could not be determined by HPLC.

3. Conclusions

In conclusion, a chiral bipyridyldiol **1** based on a zirconium complex as a catalyst for the enantioselective Strecker reaction of ketimines is described. Higher yields with moderate to good enantioselectivities were achieved for a wide range of substrates with the optimized catalyst system. The enantioselectivity of the reaction was strongly influenced by the electronic nature of the substrate. Other chiral phosphinite bipyridyl ligands **3** and **4**, however, failed to induce enantioselectivity during the reaction under different reaction conditions. A more detailed mechanistic investigation of the presented catalyst systems as well as broad catalytic studies is currently underway.

4. Experimental

4.1. 8-(Diphenyl-phosphinoyl)-10,10-dimethyl-5-pyridin-2-yl-6-aza-tricyclo[7.1.1.0^{2,7}]undeca-2(7),3,5-triene 3

A solution of **2** (2.50 g, 10.0 mmol) in THF (20 mL) was added to a LDA solution (1.1 equiv.) in THF at −40 °C under an argon atmosphere, and stirred for 2 h at the same temperature. To the resulting dark blue solution was added diphenylphosphinic chloride (3.0 mL, 10.0 mmol) dropwise. The reaction mixture was warmed to room temperature and stirred for a further 15 h. After the completion of the reaction, saturated ammonium chloride solution (20 mL) was added, and extracted with ethyl acetate (2 × 30 mL). The combined organic extracts were dried over anhydrous magnesium sulfate, filtered and the solvent was removed under reduced pressure to yield a crude product, which was purified by flash column chromatography on silica gel using ethyl acetate/hexane gradient (3:7, 1:1) as the mobile phase to afford the pure compound **3** (2.88 g, 6.4 mmol, 64%) and unreacted starting material **2** (693 mg, 2.7 mmol). ^{1}H NMR ($CDCl_3$, δ): 8.57 (s, 1H), 8.19 (s, 1H), 7.93–7.89 (t, *J* = 8.9 Hz, 2H), 7.85–7.80 (t, *J* = 8.9 Hz, 2H), 7.58–7.34 (m, 8H), 7.19 (s, 1H), 6.83–6.81 (d, *J* = 8.1 Hz, 1H), 4.40–4.36 (d, *J* = 13.7 Hz, 1H), 2.77 (s, 1H), 2.70–2.63 (m, 1H), 2.58–2.50 (m, 1H), 1.60–1.70 (d, *J* = 9.8 Hz, 1H), 1.41 (s, 3H), 0.72 (s, 3H); ^{13}C NMR ($CDCl_3$, δ): 156.0, 152.8, 151.8 (d, *J* = 6.0 Hz), 148.7, 143.0 (d, *J* = 6.0 Hz), 136.3, 135.2, 134.6, 133.9, 132.9, 132.1 (d, *J* = 9.5 Hz), 131.4 (d, *J* = 9.5 Hz), 131.2, 130.9, 128.6 (d, *J* = 11.1 Hz), 128.3 (d, *J* = 11.1 Hz), 123.1, 120.7, 118.3, 46.1 (d, *J* = 20.6 Hz), 45.3, 42.1 (d, *J* = 10.3 Hz), 41.3, 28.5, 25.8, 21.0; ^{31}P NMR ($CDCl_3$, δ): 33.1; IR (KBr): 3398, 3058, 2978, 2924, 1576, 1435, 1197, 792 cm^{-1}; MS *m/z*: 450 (M^+, 7), 435 (3), 277 (18), 249 (100), 201 (25), 77 (14); HRMS-EI *m/z* $[M]^+$ calcd for $C_{29}H_{27}N_2OP$, 450.1861; found, 450.1867.

4.2. 8-(Diphenyl-phosphinoyl)-10,10-dimethyl-5-(1-oxy-pyridin-2-yl)-6-aza-tricyclo[7.1.1.0^{2,7}]undeca-2(7),3,5-triene 6-oxide 4

To an ice-cold solution of **3** (225 mg, 0.5 mmol) in CH_2Cl_2 (10 mL) was added *m*CPBA (70%) (378 mg, 1.1 mmol) portionwise and stirred for 30 min. It was then warmed to ambient temperature and stirred for 20 h. After the completion of reaction, saturated sodium bicarbonate solution was added, and the aqueous phase was extracted with CH_2Cl_2. The extracts were dried over anhydrous magnesium sulfate, and the solvent was removed under reduced pressure to yield a crude product which was purified by flash column chromatography on Al_2O_3 using methanol/ethyl acetate gradient (0:1, 1:9) to give pure **4** (204 mg, 0.42 mmol, 84%). ^{1}H NMR ($CDCl_3$, δ): 9.00–8.97 (d, *J* = 8.1 Hz, 1H), 8.19–8.17 (d, *J* = 6.4 Hz, 1H), 7.89–7.82 (m, 4H), 7.54–7.44 (m, 6H), 7.37–7.34 (d, *J* = 8.0 Hz, 1H), 7.08–7.04 (t, *J* = 7.0 Hz, 1H), 6.83–6.75 (m, 2H), 4.36–4.31 (d, *J* = 12.7 Hz, 1H), 2.82–2.78 (t, *J* = 5.5 Hz, 1H), 2.58–2.55 (m, 2H), 1.85–1.78 (d, *J* = 9.2 Hz, 1H), 1.40 (s, 3H), 0.70 (s, 3H); ^{13}C NMR ($CDCl_3$, δ): 151.9 (d, *J* = 6.9 Hz), 146.8, 145.8, 144.0 (d, *J* = 4.7 Hz), 140.7, 134.7, 134.2, 134.0, 133.7, 133.2, 131.9 (d, *J* = 8.9 Hz), 131.3, 131.1 (d, *J* = 8.6 Hz), 128.7 (d, *J* = 11.5 Hz), 128.4 (d, *J* = 1.5 Hz), 127.6, 127.4, 125.2, 124.1, 123.3, 46.1, 45.5 (d, *J* = 68.6 Hz), 42.0 (d, *J* = 11.0 Hz), 42.1, 28.4, 25.8, 21.0; ^{31}P NMR ($CDCl_3$, δ): 33.0; IR (KBr): 3101, 2865, 2344, 1738, 1437, 1187, 996 cm^{-1}; MS *m/z*: 482 (M^+, 0.2), 466 (5), 449 (26), 405 (11), 265 (14), 249 (100), 207 (39), 77 (20); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{29}H_{27}N_2O_3P$, 428.1759; found, 428.1762.

4.3. General procedure for the preparation of *N*-diphenylphosphinoyl ketimines 5a–25a

To a solution of $NH_2OH{\cdot}HCl$ (2.1 g, 30 mmol) and NaOAc (2.5 g, 30 mmol) in EtOH/H_2O (16 mL, 1:1) was added ketones (20 mmol) at room temperature, and then refluxed for 20 h. After cooling to room temperature, the reaction mixture was stored at −20 °C for 24 h. The precipitated oxime **5**–**25** was filtered, washed with cold aqueous ethanol, vacuum dried and used directly for further reaction without purification. To a solution of oxime (10 mmol) in dichloromethane/*n*-hexane (30 mL, 1:1) was added triethylamine (1.5 mL, 10 mmol) at −40 °C, and stirred for 10 min followed by the addition of chlorodiphenylphosphine (2 mL, 10 mmol) dropwise. After stirring at −40 °C for 1 h and room temperature for 15 h, the solvents were removed under reduced pressure. Water (20 mL) was added to the residue, and then extracted with dichloromethane (2 × 30 mL). The extracts were dried over anhydrous magnesium sulfate, and the solvent was removed under reduced pressure to yield a crude product which was purified by flash column chromatography to give pure ketimines **5a**–**25a**.

4.3.1. Diphenyl-*N*-[(*E*)-1-phenylethylidene]phosphinic amide 5a

^{1}H NMR (400 MHz, $CDCl_3$, δ): 8.10–8.07 (m, 2H), 8.01–7.95 (m, 4H), 7.56–7.40 (m, 9H), 2.97 (d, J = 2.0 Hz, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 198.2, 137.6, 137.0, 136.1, 133.1, 131.8, 131.7, 131.0, 130.9, 130.3, 128.6, 128.5, 128.4, 128.3, 128.0, 127.9, 26.6; ^{31}P NMR (162 MHz, $CDCl_3$, δ): 18.8; IR (KBr): 3307, 3065, 2899, 1895, 1698, 1494, 1210, 951 cm^{-1}; MS *m/z*: 320 (M^+, 5), 217 (100), 199 (68), 152 (12), 77 (47); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{20}H_{18}NOP$, 319.1126; found, 319.1126.

4.3.2. *N*-[(*E*)-1-(2-Methoxyphenyl)ethylidene]diphenylphosphinic amide 6a

^{1}H NMR (400 MHz, $CDCl_3$, δ): 7.98–7.93 (m, 4H), 7.64 (d, J = 7.6 Hz, 1H), 7.46–7.38 (m, 7H), 7.01–6.98 (t, J = 7.4 Hz, 1H), 6.93 (d, J = 8.3 Hz, 1H), 3.80 (s, 3H), 2.88 (d, J = 1.9 Hz, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 185.0 (d, J = 7.7 Hz), 157.9, 135.3, 134.0, 132.2, 131.9, 131.7, 131.6, 131.4, 131.3 (d, J = 2.4 Hz), 131.1, 129.8, 128.4, 128.3, 120.5, 111.4, 55.4, 28.2 (d, J = 13.0 Hz); ^{31}P NMR (162 MHz, $CDCl_3$, δ): 18.4; IR (KBr): 3306, 3229, 3071, 2835, 2309, 1967, 1830, 1619, 1435, 1121, 827 cm^{-1}; MS *m/z*: 349 (M^+, 1), 216 (100), 199 (89), 140 (62), 124 (67), 77 (73); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{21}H_{20}NO_2P$, 349.1232; found, 349.1228.

4.3.3. *N*-[(*E*)-1-(3-Methoxyphenyl)ethylidene]diphenylphosphinic amide 7a

^{1}H NMR (400 MHz, $CDCl_3$, δ): 8.00–7.94 (m, 4H), 7.65–7.63 (m, 2H), 7.47–7.37 (m, 7H), 7.10 (d, J = 8.1 Hz, 1H), 3.88 (s, 3H), 2.95 (d, J = 2.0 Hz, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 181.4 (d, J = 7.7 Hz), 159.7, 140.9 (d, J = 23.9 Hz), 138.4, 135.2, 133.9, 132.6, 132.5, 132.2, 132.0, 131.8, 131.7, 131.6, 131.5, 131.4 (d, J = 2.5 Hz), 129.5, 128.5, 128.3, 121.1, 120.1, 119.6, 117.7, 113.4, 112.3, 55.4, 23.2 (d, J = 12.5 Hz); ^{31}P NMR (162 MHz, $CDCl_3$, δ): 18.8; IR (KBr): 3342, 3235, 3058, 2940, 2346, 1975, 1824, 1682, 1637, 1437, 896 cm^{-1}; MS *m/z*: 349 (M^+, 5), 216 (100), 199 (92), 140 (41), 124 (41), 77 (42); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{21}H_{20}NO_2P$, 349.1232; found, 349.1229.

4.3.4. *N*-[(*E*)-1-(4-Methoxyphenyl)ethylidene]diphenylphosphinic amide 8a

^{1}H NMR (400 MHz, $CDCl_3$, δ): 8.09 (d, J = 8.3 Hz, 2H), 7.99–7.94 (m, 4H), 7.43–7.41 (m, 6H), 6.96 (d, J = 8.2 Hz, 2H), 3.87 (s, 3H), 2.91 (s, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 180.5 (d, J = 7.2 Hz), 163.2, 135.8, 134.5, 132.4, 132.1, 131.8, 131.6, 131.5, 131.2, 130.1, 128.4, 128.2, 113.7, 55.5, 22.8 (d, J = 12.9 Hz); ^{31}P NMR (162 MHz, $CDCl_3$, δ): 18.4; IR (KBr): 3266, 3127, 1675, 1601, 1436, 1259, 1174, 915 cm^{-1}; MS *m/z*: 349 (M^+, 9), 216 (99), 199 (100), 140 (31), 124 (35), 77 (64); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{21}H_{20}NO_2P$, 349.1232; found, 349.1227.

4.3.5. *N*-[(*E*)-1-(2-Methylphenyl)ethylidene]diphenylphosphinic amide 9a

^{1}H NMR (400 MHz, $CDCl_3$, δ): 7.94–7.90 (m, 4H), 7.49–7.39 (m, 7H), 7.31–7.29 (m, 1H), 7.23–7.20 (m, 2H), 2.85 (d, J = 2.0 Hz, 3H), 2.35 (s, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 187 (d, J = 9.5 Hz), 142.2, 142.0, 135.2, 134.8, 133.5, 131.9, 131.8, 131.7, 131.6, 131.5, (d, J = 2.7 Hz), 131.3, 129.7, 128.8, 128.7, 128.5, 128.3, 127.2, 125.8, 27.9 (d, J = 13.6 Hz), 20.8; ^{31}P NMR (162 MHz, $CDCl_3$, δ): 19.1; IR (KBr): 3436, 3057, 1967, 1637, 1438, 1195, 829 cm^{-1}; MS *m/z*: 333 (M^+, 8), 318 (32), 201 (76), 153 (22), 132 (100), 77 (24); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{21}H_{20}NOP$, 333.1283; found, 333.1278.

4.3.6. *N*-[(*E*)-1-(3-Methylphenyl)ethylidene]diphenylphosphinic amide 10a

^{1}H NMR (400 MHz, $CDCl_3$, δ): 8.00–7.93 (m, 4H), 7.86 (s, 1H), 7.49–7.40 (s, 1H), 7.37 (d, J = 4.8 Hz, 2H), 2.95 (d, J = 2.2 Hz, 3H), 2.44 (s, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 181.9 (d, J = 7.6 Hz), 138.2, 135.3, 133.2, 131.9, 131.8, 131.7, 131.6, 131.5, 131.4, 131.3 (d, J = 2.3 Hz), 128.5, 128.4, 128.3, 128.2, 128.1, 125.2, 26.7, 23.2 (d, J = 12.6 Hz); ^{31}P NMR (162 MHz, $CDCl_3$, δ): 18.9; IR (KBr): 3228, 3054, 2919, 2322, 1978, 1680, 1634, 1438, 1282, 1106, 886 cm^{-1}; MS *m/z*: 333 (M^+, 4), 216 (100), 199 (70), 140 (23), 124 (24), 77 (40); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{21}H_{20}NOP$, 333.1283; found, 333.1291.

4.3.7. *N*-[(*E*)-1-(4-Methylphenyl)ethylidene]diphenylphosphinic amide 11a

^{1}H NMR (400 MHz, $CDCl_3$, δ): 7.42–7.39 (m, 6H), 7.27 (d, J = 8.1 Hz, 2H), 2.93 (d, J = 2.0 Hz, 3H), 2.40 (s, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 181.4 (d, J = 7.6 Hz), 143.2, 137.0, 136.8, 135.6, 134.3, 131.6, 131.5, 131.3 (d, J = 1.6 Hz), 129.2, 128.4, 128.3, 128.0, 23.0 (d, J = 12.9 Hz), 21.5; ^{31}P NMR (162 MHz, $CDCl_3$, δ): 18.6; IR (KBr): 3255, 3126, 2925, 1906, 1688, 1579, 1436, 1175, 914 cm^{-1}; MS *m/z*: 333 (M^+, 12), 216 (100), 199 (71), 140 (26), 124 (34), 77 (36); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{21}H_{20}NOP$, 333.1283; found, 333.1284.

4.3.8. *N*-[(*E*)-1-(2-Bromophenyl)ethylidene]diphenylphosphinic amide 12a

^{1}H NMR (400 MHz, $CDCl_3$, δ): 7.95–7.90 (m, 4H), 7.56–7.22 (m, 10H), 2.83 (d, J = 1.7 Hz, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 186 (d, J = 8.4 Hz), 143.9, 143.6, 134.3, 133.2, 133.0, 132.1, 131.7, 131.6, 131.5 (d, J = 2.0 Hz), 130.4, 128.5, 128.4, 128.3, 128.1, 127.4, 118.7, 28.3 (d, J = 14.1 Hz); ^{31}P NMR (162 MHz, $CDCl_3$, δ): 19.6; IR (KBr): 3433, 3056, 1968, 1824, 1649, 1438, 1026, 809 cm^{-1}; MS *m/z*: 400 (M^++2, 100), 398 (M^+, 99), 318 (47), 201 (85), 154 (78), 136 (63), 89 (25), 55 (43); HRMS-FAB (*m/z*): $[M+1]^+$ calcd for $C_{20}H_{18}BrNOP$, 398.0309; found, 398.0304.

4.3.9. *N*-[(*E*)-1-(3-Bromophenyl)ethylidene]diphenylphosphinic amide 13a

^{1}H NMR (400 MHz, $CDCl_3$, δ): 8.12 (s, 1H), 7.98–7.93 (m, 5H), 7.67 (d, J = 8.0 Hz, 1H), 7.50–7.42 (m, 6H), 7.37–7.33 (t, J = 8.0 Hz, 1H), 2.94 (s, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 180.9 (d, J = 7.5 Hz), 141.4, 141.1, 135.2, 134.8, 135.5, 131.8, 131.7, 131.6, 131.5, 130.8, 130.1, 128.6, 128.5, 128.4, 126.5, 122.8, 23.0 (d, J = 12.3 Hz); ^{31}P NMR (162 MHz, $CDCl_3$, δ): 19.3; IR (KBr): 3234, 3123, 3055, 1963, 1818, 1686, 1642, 1438, 994, 834 cm^{-1}; MS *m/z*: 400 (M^++2, 25), 398 (M^+, 24), 216 (94), 201 (100), 199 (78),

140 (28), 125 (35), 77 (50); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{20}H_{17}BrNOP$, 397.0231; found, 397.0239.

4.3.10. *N*-[(*E*)-1-(4-Bromophenyl)ethylidene]diphenylphosphinic amide 14a

^1H NMR (400 MHz, $CDCl_3$, δ): 7.97–7.92 (m, 6H), 7.61 (d, J = 8.3 Hz, 2H), 7.47–7.44 (m, 6H), 2.93 (s, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 180 (d, J = 7.2 Hz), 138.4, 138.2, 135.1, 133.8, 131.8, 131.6, 131.5, 129.4, 128.5, 128.4, 127.4, 22.9 (d, J = 14.1 Hz); ^{31}P NMR (162 MHz, $CDCl_3$, δ): 19.1; IR (KBr): 3255, 3126, 1673, 1617, 1579, 1436, 1175, 914 cm^{-1}; MS *m/z*: 400 (M^++2, 35), 398 (M^+, 36), 201 (100), 125 (38), 77 (24); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{20}H_{17}BrNOP$, 397.0231; found, 397.0235.

4.3.11. *N*-[(*E*)-1-(3-Chlorophenyl)ethylidene]diphenylphosphinic amide 15a

^1H NMR (400 MHz, $CDCl_3$, δ): 8.03 (s, 1H), 7.98–7.91 (m, 5H), 7.51–7.38 (m, 8H), 2.94 (d, J = 1.2 Hz, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 180.1 (d, J = 7.5 Hz), 141.2, 140.9, 134.9, 133.0, 132.2, 131.8, 131.7, 131.6, 131.5, 129.8, 128.6, 128.5, 128.4, 127.9, 126.1, 23.0 (d, J = 12.2 Hz); ^{31}P NMR (162 MHz, $CDCl_3$, δ): 19.4; IR (KBr): 3229, 3056, 2924, 2854, 1687, 1641, 1438, 1211, 848 cm^{-1}; MS *m/z*: 355 (M^++2, 7), 353 (M^+, 19), 216 (100), 199 (61), 140 (26), 124 (29), 77 (34); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{20}H_{17}ClNOP$, 353.0736; found, 353.0737.

4.3.12. *N*-[(*E*)-1-(4-Chlorophenyl)ethylidene]diphenylphosphinic amide 16a

^1H NMR (400 MHz, $CDCl_3$, δ): 8.02–7.93 (m, 6H), 7.49–7.43 (m, 8H), 2.94 (s, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 180.2 (d, J = 7.5 Hz), 138.8, 138.0, 137.7, 135.2, 133.9, 132.1, 129.6, 129.3, 128.8, 128.5, 128.4, 22.9 (d, J = 12.9 Hz); ^{31}P NMR (162 MHz, $CDCl_3$, δ): 19.1; IR (KBr): 3067, 1641, 1587, 1438, 1197, 731 cm^{-1}; MS *m/z*: 355 (M^++2, 18), 353 (M^+, 52), 311 (20), 276 (11), 201 (100), 125 (51), 77 (39); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{20}H_{17}ClNOP$, 353.0736; found, 353.0735.

4.3.13. Diphenyl-*N*-[(*E*)-1-phenylpropylidene]phosphinic amide 17a

^1H NMR (400 MHz, $CDCl_3$, δ): 8.06–7.96 (m, 6H), 7.54–7.42 (m, 9H), 3.45–3.39 (m, 2H), 1.23 (t, J = 7.8 Hz, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 186.7 (d, J = 7.7 Hz), 138.2, 137.9, 135.7, 134.4, 132.2, 131.6, 131.5, 131.3, 128.6, 128.4, 128.3, 128.2, 29.8 (d, J = 12.0 Hz), 13.1; ^{31}P NMR (162 MHz, $CDCl_3$, δ): 17.6; IR (KBr): 3612, 3255, 3126, 1906, 1738, 1616, 1579, 1436, 1175, 914 cm^{-1}; MS *m/z*: 333 (M^+, 23), 306 (13), 217 (41), 201 (100), 199 (45), 132 (22), 77 (56); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{21}H_{20}NOP$, 333.1283; found, 333.1286.

4.3.14. Diphenyl-*N*-[(*E*)-1-phenylbutylidene]phosphinic amide 18a

^1H NMR (400 MHz, $CDCl_3$, δ): 8.06–7.96 (m, 6H), 7.56–7.40 (m, 9H), 3.42–3.37 (t, J = 8.0 Hz, 2H), 1.66–1.61 (m, 2H), 0.97 (t, J = 7.0 Hz, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 185.0 (d, J = 7.0 Hz), 138.6, 138.3, 135.7, 134.4, 132.2, 132.1, 132.0, 131.6, 131.5, 131.3 (d, J = 3.0 Hz), 130.2, 128.6, 128.5, 128.4, 128.3, 128.2, 127.1, 37.7 (d, J = 11.3 Hz), 22.4, 14.2; ^{31}P NMR (162 MHz, $CDCl_3$, δ): 17.6; IR (KBr): 3431, 3052, 2957, 2872, 1964, 1913, 1827, 1635, 1437, 1287, 814 cm^{-1}; MS *m/z*: 347 (M^+, 52), 319 (21), 216 (18), 201 (100), 199 (17), 146 (65), 77 (54); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{22}H_{22}NOP$, 347.1439; found, 347.1433.

4.3.15. *N*-[(*E*)-2-Methyl-1-phenylpropylidene]diphenylphosphinic amide 19a

^1H NMR (400 MHz, $CDCl_3$, δ): 7.94–7.88 (m, 4H), 7.48–7.31 (m, 1H), 3.52–3.45 (m, 1H), 1.30 (d, J = 6.9 Hz, 6H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 193.1 (d, J = 10.1 Hz), 139.4, 139.3, 135.7, 134.4, 132.4, 132.3, 131.9, 131.7, 131.6, 131.2 (d, J = 2.5 Hz), 130.3, 128.8, 128.3, 127.8, 127.5, 39.8 (d, J = 16.6 Hz), 20.6; ^{31}P NMR (162 MHz, $CDCl_3$, δ): 14.9; IR (KBr): 3166, 3058, 2910, 2853, 1964, 1825, 1680, 1641, 1438, 914 cm^{-1}; MS *m/z*: 347 (M^+, 2), 304 (0.3), 201 (100), 146 (22), 77 (21); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{22}H_{22}NOP$, 347.1439; found, 347.1431.

4.3.16. Diphenyl-*N*-[(*E*)-1-phenylmethylidene]phosphinic amide 20a

^1H NMR (400 MHz, $CDCl_3$, δ): 9.36 (d, J = 32.0 Hz, 1H), 8.00–7.90 (m, 6H), 7.49–7.43 (m, 9H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 173.8 (d, J = 7.7 Hz), 135.9, 135.7, 135.6, 132.4, 132.3, 132.0, 131.8 (d, J = 2.2 Hz), 131.6, 131.5, 130.1, 128.9, 128.7, 128.6, 128.5, 128.4; ^{31}P NMR (162 MHz, $CDCl_3$, δ): 24.8; IR (KBr): 3233, 3125, 3056, 2881, 1906, 1625, 1438, 1127, 832 cm^{-1}; MS *m/z*: 305 (M^++2, 18), 216 (100), 199 (64), 140 (26), 124 (31), 77 (33); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{19}H_{16}NOP$, 305.0970; found, 305.0974.

4.3.17. *N*-[(*E*)-1-(1-Naphthyl)ethylidene]diphenylphosphinic amide 21a

^1H NMR (400 MHz, $CDCl_3$, δ): 8.14 (d, J = 8.5 Hz, 1H), 7.99–7.87 (m, 6H), 7.62–7.38 (m, 10H), 3.03 (d, J = 2.1 Hz, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 186.3 (d, J = 9.2 Hz), 140.1, 139.9, 134.7, 133.7, 133.0, 132.2, 131.9, 131.8, 131.7, 131.5, 130.7, 129.6, 128.8, 128.7, 128.5, 128.4, 126.8, 126.2, 126.1, 125.5, 28.4 (d, J = 13.3 Hz); ^{31}P NMR (162 MHz, $CDCl_3$, δ): 18.7; IR (KBr): 3423, 3057, 2224, 1824, 1642, 1438, 1122, 853 cm^{-1}; MS *m/z*: 369 (M^+, 1), 216 (100), 199 (70), 155 (28), 124 (24), 77 (34); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{24}H_{20}NOP$, 369.1283; found, 369.1286.

4.3.18. *N*-[(*E*)-1-(2-Naphthyl)ethylidene]diphenylphosphinic amide 22a

^1H NMR (400 MHz, $CDCl_3$, δ): 8.45 (s, 1H), 8.29 (d, J = 8.7 Hz, 1H), 8.04–7.88 (m, 7H), 7.60–7.41 (m, 8H), 3.08 (d, J = 2.0 Hz, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 181.3 (d, J = 7.6 Hz), 136.9, 136.6, 135.4, 135.2, 134.1, 132.6, 131.8, 131.7, 131.6, 131.5, 131.4 (d, J = 2.3 Hz), 129.5, 129.4, 128.5, 128.4, 128.3, 127.7, 126.7, 124.1, 23.1 (d, J = 12.5 Hz); ^{31}P NMR (162 MHz, $CDCl_3$, δ): 18.9; IR (KBr): 3230, 3121, 3041, 2922, 1967, 1818, 1677, 1623, 1438, 1194, 994 cm^{-1}; MS *m/z*: 369 (M^+, 69), 327 (14), 292 (18), 201 (100), 125 (23), 77 (13); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{24}H_{20}NOP$, 369.1283; found, 369.1279.

4.3.19. *N*-[(*E*)-1-(2-Furyl)ethylidene]diphenylphosphinic amide 23a

^1H NMR (400 MHz, $CDCl_3$, δ): 7.98–7.93 (m, 4H), 7.61 (s, 1H), 7.47–7.39 (m, 6H), 7.24 (d, J = 3.4 Hz, 1H), 6.55–6.54 (m, 1H), 2.80 (d, J = 1.9 Hz, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 170.2 (d, J = 10.1 Hz), 154.6, 154.3, 146.4, 135.5, 134.2, 131.6, 131.5, 131.3 (d, J = 2.3 Hz), 128.4, 128.3, 116.3, 112.5, 22.2 (d, J = 16.6 Hz); ^{31}P NMR (162 MHz, $CDCl_3$, δ): 19.5; IR (KBr): 3612, 3247, 3127, 1908, 1617, 1579, 1436, 1125, 915 cm^{-1}; MS *m/z*: 309 (M^+, 0.7), 216 (100), 199 (78), 140 (35), 124 (42), 77 (41); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{18}H_{16}NO_2P$, 309.0919; found, 309.0923.

4.3.20. Diphenyl-*N*-[(*E*)-1-(3-thienyl)ethylidene]phosphinic amide 24a

^1H NMR (400 MHz, $CDCl_3$, δ): 7.99–7.92 (m, 5H), 7.74 (d, J = 5.2 Hz, 1H), 7.45–7.40 (m, 6H), 7.34–7.32 (m, 1H), 2.88 (s, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 176.0 (d, J = 7.3 Hz), 144.6, 144.4, 135.5, 134.2, 131.6, 131.5, 131.3, 130.7, 128.4, 128.3, 127.1, 126.2, 23.8 (d, J = 12.6 Hz). ^{31}P NMR (162 MHz, $CDCl_3$, δ): 18.9; IR (KBr): 3295, 3232, 3124, 1968, 1903, 1667, 1628, 1437, 1264, 1175, 914 cm^{-1}; MS *m/z*: 325 (M^+, 0.5), 216 (100), 199

(63), 140 (19), 124 (27), 77 (26); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{18}H_{16}NOPS$, 325.0690; found, 325.0685.

4.3.21. Diphenyl-*N*-[(*E*)-1-(3-pyridyl)ethylidene]phosphinic amide 25a

^1H NMR (400 MHz, $CDCl_3$, δ): 9.29 (d, J = 1.8 Hz, 1H), 8.75 (d, J = 4.7 Hz, 1H), 8.32 (d, J = 7.8 Hz, 1H), 8.00–7.94 (m, 3H), 7.48–7.39 (m, 7H), 2.98 (d, J = 2.0 Hz, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 179.5 (d, J = 7.4 Hz), 152.7, 149.4, 135.0, 134.8, 133.5, 131.6, 131.5, 128.5, 123.3, 22.9 (d, J = 13.1 Hz); ^{31}P NMR (162 MHz, $CDCl_3$, δ): 19.3; IR (KBr): 3247, 3128, 1906, 1688, 1587, 1437, 1175, 915 cm^{-1}; MS *m/z*: 320 (M^+, 0.3), 216 (100), 199 (67), 140 (26), 124 (29), 77 (29); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{19}H_{17}N_2OP$, 320.1079; found, 320.1074.

4.4. General procedure for the Strecker synthesis of N-substituted α-aminonitriles (5b–25b)

To a solution of chiral ligand **1** (7.0 mg, 0.01 mmol) in THF (1.5 mL) was added $Zr(Ot\text{-}Bu)_4$ (4 μL, 0.01 mmol) dropwise, and stirred at room temperature for 1 h. Ketimines (**5a**–**25a**) (0.1 mmol) and TMSCN (0.1 mmol) were then added successively and the solution was stirred at −30 °C for 72 h. The reaction mixture was then passed through silica gel column, and eluted with ethyl acetate. The concentrated residues were purified by flash column chromatography on silica gel to afford pure products (**5b**–**25b**).

4.4.1. *N*-[1-Cyano-1-(2-methoxyphenyl)ethyl]diphenylphosphinic amide 6b

$[\alpha]_D^{23} = -2.15$ (*c* 1.3, CH_2Cl_2); ^1H NMR (400 MHz, $CDCl_3$, δ): 7.97–7.02 (m, 2H), 7.75–7.69 (m, 2H), 7.54–7.34 (m, 8H), 7.00 (d, J = 7.2 Hz, 2H), 4.72 (d, J = 8.4 Hz, 2H), 3.93 (s, 3H), 2.09 (s, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 156.8, 134.2, 133.7, 132.9, 132.4, 132.1, 132.0, 131.9, 131.4, 131.3, 130.5, 128.7, 128.6 (d, J = 2.9 Hz), 128.4, 128.2, 125.8, 121.7 (d, J = 5.0 Hz), 121.3, 112.2, 55.9, 52.4, 24.9; ^{31}P NMR (162 MHz, $CDCl_3$, δ): 20.4; IR (KBr): 3389, 3105, 2885, 1587, 1486, 1436, 1193, 992 cm^{-1}; MS *m/z*: 376 (M^+, 1), 318 (62), 201 (100), 148 (18), 77 (31); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{22}H_{22}N_2O_2P$, 376.1340; found, 376.1348; HPLC (Daicel Chiralcel OJ, hexane/*i*-PrOH = 90:10, flow rate 0.75 mL/min) t_R 16.3 and 25.7 min.

4.4.2. *N*-[1-Cyano-1-(3-methoxyphenyl)ethyl]diphenylphosphinic amide 7b

$[\alpha]_D^{23} = -4.9$ (*c* 1.6, CH_2Cl_2); ^1H NMR (400 MHz, $CDCl_3$, δ): 8.04–7.99 (m, 2H), 7.84–7.99 (m, 2H), 7.56–7.39 (m, 6H), 7.32–7.29 (m, 3H), 6.87–6.85 (m, 1H), 3.83 (s, 3H), 3.74 (br, 1H), 1.92 (s, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 160.0, 142.7 (d, J = 3.3 Hz), 133.5, 132.8, 132.4, 132.3, 132.2, 131.5, 131.4, 131.3, 130.1, 128.9, 128.1, 128.7, 128.6, 121.3 (d, J = 4.4 Hz), 117.4, 114.6, 111.0, 56.9, 55.4, 29.4; ^{31}P NMR (162 MHz, $CDCl_3$, δ): 20.5; IR (KBr): 3131, 3056, 2873, 1738, 1599, 1436, 1263, 1194, 865 cm^{-1}; MS *m/z*: 376 (M^+, 37), 307 (49), 201 (11), 125 (11), 77 (29); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{22}H_{22}N_2O_2P$, 376.1340; found, 376.1337; HPLC (Daicel Chiralcel OJ, hexane/*i*-PrOH = 90:10, flow rate 0.5 mL/min) t_R 19.9 and 35.0 min.

4.4.3. *N*-[1-Cyano-1-(4-methoxyphenyl)ethyl]diphenylphosphinic amide 8b

$[\alpha]_D^{23} = -2.35$ (*c* 0.85, CH_2Cl_2); ^1H NMR (400 MHz, $CDCl_3$, δ): 8.03–7.97 (m, 2H), 7.83–7.82 (m, 2H), 6.42–6.19 (d, J = 6.7 Hz, 2H), 7.54–7.41 (m, 6H), 6.88–6.86 (d, J = 6.8 Hz, 2H), 3.79 (s, 3H), 3.69 (d, J = 7.6 Hz, 1H), 1.91 (s, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 159.9, 133.6, 133.0 (d, J = 4.0 Hz), 132.3, 132.4, 132.1 (d, J = 2.2 Hz), 131.6, 131.4, 131.3, 128.8, 128.7, 128.5, 126.4, 121.5 (d, J = 4.1 Hz), 114.2, 56.3, 55.3, 29.6 (d, J = 3.5 Hz); ^{31}P NMR (162 MHz, $CDCl_3$, δ): 20.2; IR (KBr): 3160, 3077, 2873, 1738, 1609, 1510, 1253, 1192, 995 cm^{-1}; MS *m/z*: 376 (M^+, 12), 349 (67), 307 (21), 201 (100), 125 (32), 125 (32), 77 (31); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{22}H_{22}N_2O_2P$, 376.1340; found, 376.1337; HPLC (Daicel Chiralcel OJ, hexane/*i*-PrOH = 90:10, flow rate 0.5 mL/min) t_R 33.1 and 58.9 min.

4.4.4. *N*-[1-Cyano-1-(2-methylphenyl)ethyl]diphenylphosphinic amide 9b

$[\alpha]_D^{23} = -2.7$ (*c* 2.0, CH_2Cl_2); ^1H NMR (400 MHz, $CDCl_3$, δ): 8.06–8.01 (m, 2H), 7.83–7.77 (m, 2H), 7.65–7.63 (d, J = 7.6 Hz, 2H), 7.56–7.39 (m, 6H), 7.42–7.18 (3H), 3.65 (d, J = 7.3 Hz, 1H), 2.71 (s, 3H), 2.11 (s, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 137.1, 135.8, 133.4, 133.1, 132.5, 132.4, 132.2, 131.4, 131.4, 131.0, 129.2, 128.7 (d, J = 3.4 Hz), 128.6, 126.5, 126.0, 121.5, 55.6, 27.6 (d, J = 3.4 Hz), 21.3; ^{31}P NMR (162 MHz, $CDCl_3$, δ): 19.9; IR (KBr): 3425, 3108, 2875, 1742, 1591, 1436, 1169, 988 cm^{-1}; MS *m/z*: 360 (M^+, 0.8), 333 (16), 318 (13), 201 (100), 159 (25), 132 (73), 77 (28); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{22}H_{21}N_2OP$, 360.1391; found, 360.1385; HPLC (Daicel Chiralcel OJ, hexane/*i*-PrOH = 90:10, flow rate 0.5 mL/min) t_R 20.4 and 26.9 min.

4.4.5. *N*-[1-Cyano-1-(3-methylphenyl)ethyl]diphenylphosphinic amide 10b

$[\alpha]_D^{23} = -1.7$ (*c* 1.05, CH_2Cl_2); ^1H NMR (400 MHz, $CDCl_3$, δ): 8.06–8.00 (m, 2H), 7.85–7.80 (m, 2H), 7.57–7.42 (m, 8H), 7.31–7.27 (t, J = 7.6 Hz, 1H), 7.15 (d, J = 7.5 Hz, 1H), 3.69 (d, J = 7.3 Hz, 1H), 2.36 (s, 3H), 1.92 (s, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 141.0 (d, J = 3.8 Hz), 138.9, 133.5, 132.8, 132.4, 132.3 (d, J = 5.0 Hz), 131.5, 131.4, 131.3, 129.7, 129.0, 128.9, 128.8, 128.7, 128.6, 125.9, 122.4, 121.5, 56.8, 29.5, 21.5; ^{31}P NMR (162 MHz, $CDCl_3$, δ): 20.3; IR (KBr): 3426, 3104, 2879, 1591, 1436, 1126, 993 cm^{-1}; MS *m/z*: 360 (M^+, 12), 333 (25), 291 (21), 201 (100), 125 (17), 77 (28); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{22}H_{21}N_2OP$, 360.1391; found, 360.1397; HPLC (Daicel Chiralcel OJ, hexane/*i*-PrOH = 90:10, flow rate 0.5 mL/min) t_R 13.3 and 17.4 min.

4.4.6. *N*-[1-Cyano-1-(4-methylphenyl)ethyl]diphenylphosphinic amide 11b

$[\alpha]_D^{23} = -1.7$ (*c* 1.05, CH_2Cl_2); ^1H NMR (400 MHz, $CDCl_3$, δ): 8.06–8.00 (m, 2H), 7.85–7.80 (m, 2H), 7.63 (d, J = 8.2 Hz, 2H), 7.57–7.42 (m, 6H), 7.20 (d, J = 8.0 Hz, 2H), 3.61 (d, J = 8.0 Hz, 1H), 2.34 (s, 3H), 1.92 (s, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 139.0, 138.3, 132.4, 132.3, 131.4, 131.2, 129.6, 128.9, 128.8, 128.7, 128.6, 125.2, 121.5 (d, J = 3.8 Hz), 56.7, 29.4, 21.0; ^{31}P NMR (162 MHz, $CDCl_3$, δ): 20.2; IR (KBr): 3099, 2880, 1738, 1436, 1377, 1190, 995 cm^{-1}; MS *m/z*: 360 (M^+, 27), 345 (7), 333 (17), 291 (66), 201 (100), 125 (28), 77 (32); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{22}H_{21}N_2OP$, 360.1391; found, 360.1395; HPLC (Daicel Chiralcel OJ, hexane/*i*-PrOH = 100:1, flow rate 1.0 mL/min) t_R 20.6 and 26.2 min.

4.4.7. *N*-[1-(2-Bromophenyl)-1-cyanoethyl]diphenylphosphinic amide 12b

$[\alpha]_D^{23} = -1.3$ (*c* 1.15, CH_2Cl_2); ^1H NMR (400 MHz, $CDCl_3$, δ): 7.99–7.94 (m, 2H), 7.80–7.75 (m, 2H), 7.66–7.63 (d, J = 7.8 Hz, 2H), 7.59–7.46 (m, 5H), 7.40–7.38 (m, 2H), 7.32 (t, J = 7.1 Hz, 1H), 4.4 (d, J = 3.6 Hz, 1H), 2.23 (s, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 137.5 (d, J = 3.0 Hz), 235.5, 133.3, 132.8, 132.4, 132.1, 132.0, 131.5, 131.4, 130.6, 128.8, 128.7, 128.5, 128.1, 127.8, 121.5, 120.3 (d, J = 5.4 Hz), 55.3, 26.6 (d, J = 4.1 Hz); ^{31}P NMR (162 MHz, $CDCl_3$, δ): 20.5; IR (KBr): 3427, 3063, 2872, 1728, 1591, 1463, 1436, 1125, 993 cm^{-1}; MS *m/z*: 426 (M^++2, 0.5), 424 (M^+, 0.5), 345 (95), 318 (100), 277 (10), 201 (98), 183 (23), 152 (15), 77(65); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{21}H_{18}BrN_2OP$, 424.0340; found, 424.0338.

4.4.8. *N*-[1-(3-Bromophenyl)-1-cyanoethyl]diphenylphosphinic amide 13b

$[\alpha]_D^{23} = -4.6$ (*c* 1.4, CH_2Cl_2); ^1H NMR (400 MHz, $CDCl_3$, δ): 7.99–7.96 (m, 2H), 7.82–7.77 (m, 2H), 7.71 (d, *J* = 7.8 Hz, 1H), 7.57–7.41 (m, 7H), 7.28–7.24 (m, 1H), 3.74 (d, *J* = 7.4 Hz, 1H), 1.93 (s, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 143 (d, *J* = 3.1 Hz), 133.2, 132.7, 132.5, 132.4, 132.3, 132.2, 131.9, 131.4, 131.3, 130.6, 128.9, 128.8, 124.3, 122.9, 120.8 (d, *J* = 4.2 Hz), 56.3, 29.6 (d, *J* = 3.8 Hz); ^{31}P NMR (162 MHz, $CDCl_3$, δ): 20.7; IR (KBr): 3433, 3079, 2877, 1591, 1471, 1737, 1125, 995 cm^{-1}; MS *m/z*: 426 (M^++2, 2.5), 424 (M^+, 2.5), 399 (4), 397 (4), 201 (100), 125 (31), 77 (31); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{21}H_{18}BrN_2OP$, 424.0340; found, 424.0335; HPLC (Daicel Chiralcel OJ, hexane/*i*-PrOH = 90:10, flow rate 0.5 mL/min) t_R 15.7 and 19.6 min.

4.4.9. *N*-[1-(4-Bromophenyl)-1-cyanoethyl]diphenylphosphinic amide 14b

$[\alpha]_D^{23} = -6.4$ (*c* 1.15, CH_2Cl_2); ^1H NMR (400 MHz, $CDCl_3$, δ): 7.98–7.94 (m, 2H), 7.79–7.74 (m, 2H), 7.59–7.41 (m, 8H), 3.90 (d, *J* = 6.8 Hz, 1H), 1.89 (s, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 140 (d, *J* = 3.2 Hz), 133.2, 132.7, 132.4, 132.3, 132.2, 132.0, 131.9, 131.3, 131.2, 128.9, 128.8, 128.7, 128.6, 127.3, 123.1, 121.0, 120.9, 56.5, 29.6 (d, *J* = 3.9 Hz); ^{31}P NMR (162 MHz, $CDCl_3$, δ): 20.8; IR (KBr): 3255, 3126, 1673, 1617, 1579, 1436, 1175, 914 cm^{-1}; MS *m/z*: 426 (M^++2, 41), 424 (M^+, 41), 357 (63), 355 (60), 201 (100), 125 (59), 77 (63); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{21}H_{18}BrN_2OP$, 424.0340; found, 424.0337; HPLC (Daicel Chiralcel OJ, hexane/*i*-PrOH = 90:10, flow rate 0.5 mL/min) t_R 25.1 and 31.2 min.

4.4.10. *N*-[1-(3-Chlorophenyl)-1-cyanoethyl]diphenylphosphinic amide 15b

$[\alpha]_D^{23} = -3.2$ (*c* 1.25, CH_2Cl_2); ^1H NMR (400 MHz, $CDCl_3$, δ): 7.98–7.93 (m, 2H), 7.80–7.75 (m, 2H), 7.65–7.63 (m, 2H), 7.55–7.47 (m, 4H), 7.43–7.40 (m, 2H), 7.31–7.29 (m, 2H), 3.94 (d, *J* = 1.8 Hz, 1H), 1.91 (s, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 142.9 (d, *J* = 3.4 Hz), 134.9, 133.2, 132.7, 132.4 (d, *J* = 2.3 Hz), 132.3, 132.2, 131.9, 131.4, 131.3, 130.3, 129.1, 128.9, 128.7 (d, *J* = 1.6 Hz), 128.6, 125.7, 123.8, 120.9 (d, *J* = 4.0 Hz), 56.4, 29.7 (d, *J* = 4.0 Hz); ^{31}P NMR (162 MHz, $CDCl_3$, δ): 20.8; IR (KBr): 3049, 3078, 2871, 1739, 1592, 1437, 1192, 1077, 996 cm^{-1}; MS *m/z*: 382 (M^++2, 2), 380 (M^+, 7), 353 (36), 311 (18), 201 (100), 125 (33), 77 (31); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{21}H_{18}ClN_2OP$, 380.0845; found, 380.0849; HPLC (Daicel Chiralcel OJ, hexane/*i*-PrOH = 90:10, flow rate 0.5 mL/min) t_R 15.7 and 19.8 min.

4.4.11. *N*-[1-(4-Chlorophenyl)-1-cyanoethyl]diphenylphosphinic amide 16b

$[\alpha]_D^{23} = -5.7$ (*c* 0.85, CH_2Cl_2); ^1H NMR (400 MHz, $CDCl_3$, δ): 8.00–7.97 (m, 2 H), 7.81–7.76 (m, 2H), 6.80 (d, *J* = 8.6 Hz, 2H), 7.56–7.50 (m, 4H), 7.44–7.41 (m, 2H), 7.34 (d, *J* = 8.6 Hz, 2H), 3.72 (br, 1H), 1.91 (s, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 139.5 (d, *J* = 2.9 Hz), 135.0, 133.2, 132.7, 132.4, 132.3, 132.0, 131.5, 131.3, 131.2, 129.1, 128.9, 128.8, 128.7, 128.6, 127.0, 121.0 (d, *J* = 4.3 Hz), 56.4, 29.6 (d, *J* = 3.9 Hz); ^{31}P NMR (162 MHz, $CDCl_3$, δ): 20.7; IR (KBr): 3421, 3109, 2875, 2232, 1905, 1736, 1592, 1490, 1437, 1188, 995 cm^{-1}; MS *m/z*: 382 (M^++2, 2), 380 (M^+, 6), 380 (6), 353 (27), 311 (19), 201 (100), 125 (28), 77 (23); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{21}H_{18}ClN_2OP$, 380.0845; found, 380.0849; HPLC (Daicel Chiralcel OJ, hexane/*i*-PrOH = 90:10, flow rate 0.5 mL/min) t_R 15.7 and 18.3 min.

4.4.12. *N*-(1-Cyano-1-phenylpropyl)diphenylphosphinic amide 17b

$[\alpha]_D^{23} = +0.9$ (*c* 1.2, CH_2Cl_2); ^1H NMR (400 MHz, $CDCl_3$, δ): 8.00–7.79 (m, 2H), 7.77–7.74 (m, 2H), 7.66 (d, *J* = 8.0 Hz, 2H), 7.55–7.45 (m, 4H), 7.41–7.32 (m, 4H), 2.36–2.30 (m, 2H), 1.23 (t, *J* = 7.2 Hz, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 138.3 (d, *J* = 3.3 Hz), 133.4, 133.0, 132.3, 132.2, 132.1 (d, *J* = 2.3 Hz), 131.7, 131.5, 131.4, 128.9, 128.8, 128.7, 128.5, 126.3, 120.2 (d, *J* = 3.6 Hz), 62.5, 34.8 (d, *J* = 3.7 Hz), 9.3; ^{31}P NMR (162 MHz, $CDCl_3$, δ): 20.3; IR (KBr): 3176, 3056, 2896, 2234, 1896, 1737, 1449, 1198, 1123, 873 cm^{-1}; MS *m/z*: 360 (M^+, 4), 333 (26), 201 (100), 132 (27), 77 (24); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{22}H_{21}N_2OP$, 360.1391; found, 360.1385; HPLC (Daicel Chiralcel OJ, hexane/*i*-PrOH = 90:10, flow rate 0.5 mL/min) t_R 12.5 and 20.1 min.

4.4.13. *N*-(1-Cyano-1-phenylbutyl)diphenylphosphinic amide 18b

$[\alpha]_D^{23} = -3.4$ (*c* 0.85, CH_2Cl_2); ^1H NMR (400 MHz, $CDCl_3$, δ): 7.99–7.93 (m, 2H), 7.78–7.73 (m, 2H), 7.64 (d, *J* = 8.0 Hz, 1H), 7.53–7.47 (m, 4H), 7.41–7.31 (m, 5H), 3.72 (d, *J* = 7.3 Hz, 1H), 2.30–2.16 (m, 2H), 1.39–1.32 (m, 1H), 0.93–0.85 (m, 1H), 0.76 (t, *J* = 7.2 Hz, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 138.6 (d, *J* = 3.3 Hz), 133.2, 132.9, 132.3, 132.2, 132.1 (d, *J* = 2.2 Hz), 131.9, 131.6, 131.5, 131.4, 128.9, 128.8, 128.7, 128.6, 128.5, 126.2, 120.5 (d, *J* = 3.5 Hz), 61.5, 43.6 (d, *J* = 3.7 Hz), 18.4, 13.4; ^{31}P NMR (162 MHz, $CDCl_3$, δ): 20.2; IR (KBr): 3199, 3060, 2962, 1731, 1590, 1437, 1124, 907 cm^{-1}; MS *m/z*: 374 (M^+, 2), 318 (12), 216 (3), 201 (100), 175 (8), 132 (8), 77 (34); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{23}H_{23}N_2OP$, 374.1548; found, 374.1544; HPLC (Daicel Chiralcel OJ, hexane/*i*-PrOH = 90:10, flow rate 0.75 mL/min) t_R 7.2 and 10.91 min

4.4.14. *N*-(1-Cyano-2-methyl-1-phenylpropyl)diphenylphosphinic amide 19b

$[\alpha]_D^{23} = -3.2$ (*c* 1.05, CH_2Cl_2); ^1H NMR (400 MHz, $CDCl_3$, δ): 7.80–7.75 (m, 2H), 7.58–7.53 (m, 2H), 7.48–7.45 (m, 1H), 7.40–7.36 (m, 5H), 7.28–7.24 (m, 2H), 7.22–7.18 (m, 3H), 4.08 (d, *J* = 5.0 Hz, 1H), 2.46–2.43 (m, 1H), 1.30 (d, *J* = 6.6 Hz, 3H), 0.74 (d, *J* = 6.7 Hz, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 136.5, 133.2, 132.1, 132.0, 131.9, 131.8 (d, *J* = 2.3 Hz), 130.5, 128.5, 128.4, 128.1, 128.0, 127.0, 118.8 (d, *J* = 2.6 Hz), 65.7 (d, *J* = 3.4 Hz), 40.6 (d, *J* = 5.0 Hz), 18.9, 17.7; ^{31}P NMR (162 MHz, $CDCl_3$, δ): 20.7; IR (KBr): 3426, 3174, 3061, 2965, 1729, 1591, 1437, 1195, 1123, 857 cm^{-1}; MS *m/z*: 374 (M^+, 13), 347 (50), 304 (18), 228 (32), 201 (100), 146 (63), 77 (63); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{23}H_{23}N_2OP$, 374.1548; found, 374.1545; HPLC (Daicel Chiralcel OJ, hexane/*i*-PrOH = 90:10, flow rate 0.5 mL/min) t_R 10.7 and 14.9 min.

4.4.15. *N*-Cyano(phenyl)methyl(diphenyl)phosphinic amide 20b

$[\alpha]_D^{23} = -0.6$ (*c* 1.2, CH_2Cl_2); ^1H NMR (400 MHz, $CDCl_3$, δ): 8.02–7.97 (m, 2H), 7.83–7.78 (m, 2H), 7.62–7.37 (m, 6H), 5.20 (d, *J* = 10.6 Hz, 1H), 4.02 (d, *J* = 8.7 Hz, 1H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 134.9, 132.7, 132.6, 132.5, 131.8, 131.7, 129.2, 129.0, 128.9, 128.8, 128.7, 127.1, 46.2; ^{31}P NMR (162 MHz, $CDCl_3$, δ): 24.6; IR (KBr): 3436, 3128, 2879, 2720, 2233, 1979, 1741, 1591, 1437, 939 cm^{-1}; MS *m/z*: 332 (M^+, 18), 305 (18), 201 (94), 155 (20), 91 (42), 77 (68); HRMS-EI (*m/z*): $[M]^+$ calcd for $C_{20}H_{17}N_2OP$, 332.1078; found, 332.1080; HPLC (Daicel Chiralcel OJ, hexane/*i*-PrOH = 90:10, flow rate 0.5 mL/min) t_R 24.3 and 27.1 min.

4.4.16. *N*-[1-Cyano-1-(1-naphthyl)ethyl]diphenylphosphinic amide 21b

$[\alpha]_D^{23} = -1.2$ (*c* 1.25, CH_2Cl_2); ^1H NMR (400 MHz, $CDCl_3$, δ): 8.97 (d, *J* = 8.7 Hz, 1H), 8.08–8.03 (m, 2H), 7.89–7.83 (m, 3H), 7.77–7.73 (m, 2H), 7.72–7.68 (t, *J* = 7.7 Hz, 1H), 7.58–7.52 (m, 4H), 7.43–7.39 (m, 2H), 7.34–7.32 (m, 2H), 3.98 (d, *J* = 8.0 Hz, 1H), 2.33 (s, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 134.8, 134.2 (d, *J* = 4.6 Hz), 133.3, 132.6, 132.5, 132.1 (d, *J* = 2.3 Hz), 131.9, 131.2, 131.1, 130.9, 130.6, 129.5, 129.0, 128.4, 128.7, 128.6, 128.4, 126.8, 126.1,

124.9, 124.7, 124.5, 121.7 (d, J = 3.0 Hz), 56.3, 27.9 (d, J = 3.0 Hz); ^{31}P NMR (162 MHz, $CDCl_3$, δ): 20.3; IR (KBr): 3106, 2980, 2865, 1739, 1591, 1437, 1187, 981 cm^{-1}; MS m/z: 396 (M^+, 3), 369 (15), 327 (59), 201 (100), 168 (89), 127 (21), 77 (28); HRMS-EI (m/z): $[M]^+$ calcd for $C_{25}H_{21}N_2OP$, 396.1391; found, 396.1385.

4.4.17. *N*-[1-Cyano-1-(2-naphthyl)ethyl]diphenylphosphinic amide 22b

$[\alpha]_D^{23} = -3.2$ (c 1.05, CH_2Cl_2); ^{1}H NMR (400 MHz, $CDCl_3$, δ): 8.13 (s, 1H), 8.08–8.02 (m, 2H), 7.90–7.80 (m, 6H), 7.55–7.39 (m, 8H), 3.75 (d, J = 7.8 Hz), 2.03 (s, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 138.1, 133.2, 132.7, 132.4, 132.3, 132.2, 131.3, 131.2, 129.4, 128.9, 128.8, 128.7, 128.6, 128.4, 127.5, 127.0, 126.8, 124.5, 122.7, 121.4, 57.0, 29.2 (d, J = 3.6 Hz); ^{31}P NMR (162 MHz, $CDCl_3$, δ): 20.4; IR (KBr): 3113, 2874, 1738, 1473, 1193, 996 cm^{-1}; MS m/z: 396 (M^+, 4), 369 (64), 327 (22), 201 (100), 125 (31), 77 (27); HRMS-EI (m/z): $[M]^+$ calcd for $C_{25}H_{21}N_2OP$, 396.1391; found, 396.1387; HPLC (Daicel Chiralcel OD-H, hexane/i-PrOH = 90:10, flow rate 0.3 mL/min) t_R 62.1 and 65.7 min.

4.4.18. *N*-[1-Cyano-1-(2-furyl)ethyl]diphenylphosphinic amide 23b

$[\alpha]_D^{23} = -2.7$ (c 0.9, CH_2Cl_2); ^{1}H NMR (400 MHz, $CDCl_3$, δ): 7.91–7.88 (m, 2H), 7.84–7.80 (m, 2H), 7.52–7.43 (m, 6H), 7.31 (s, 1H), 6.43 (d, J = 3.3 Hz, 1H), 6.26–6.25 (m, 1H), 3.80 (d, J = 6.7 Hz, 1H), 2.04 (s, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 150 (d, J = 4.5 Hz), 143.4, 133.2, 132.7, 132.2 (d, J = 8.4 Hz), 132.0, 131.9, 131.7, 131.6, 131.4, 128.7, 128.6, 128.5, 119.6 (d, J = 4.0 Hz), 110.7, 108.4, 50.3, 26.3 (d, J = 3.2 Hz); ^{31}P NMR (162 MHz, $CDCl_3$, δ): 20.4; IR (KBr): 3078, 2870, 1902, 1683, 1436, 1125, 1010, 748 cm^{-1}; MS m/z: 336 (M^+, 6), 309 (64), 201 (100), 185 (41), 77 (34); HRMS-EI (m/z): $[M]^+$ calcd for $C_{19}H_{17}N_2O_2P$, 336.1027; found, 336.1035; HPLC (Daicel Chiralcel OJ, hexane/i-PrOH = 90:10, flow rate 0.5 mL/min) t_R 26.6 and 31.4 min.

4.4.19. *N*-[1-Cyano-1-(3-thienyl)ethyl]diphenylphosphinic amide 24b

$[\alpha]_D^{23} = -0.9$ (c 1.05, CH_2Cl_2); ^{1}H NMR (400 MHz, $CDCl_3$, δ): 8.00–7.95 (m, 2H), 7.83–7.78 (m, 2H), 7.56–7.40 (m, 7H), 7.33–7.29 (m, 2H), 3.67 (d, J = 7.1 Hz, 1H), 1.97 (s, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 141.8, 133.3, 132.8, 132.4, 132.2, 132.1, 132.0, 131.4, 131.3, 128.9, 128.7 (d, J = 3.3 Hz), 128.6, 127.6, 125.4, 122.9, 121.4, 53.0, 29.1; ^{31}P NMR (162 MHz, $CDCl_3$, δ): 20.0; IR (KBr): 3103, 2917, 2867, 1738, 1592, 1435, 1191, 1009 cm^{-1}; MS m/z: 352 (M^+, 33), 325 (24), 283 (23), 201 (100), 77 (30); HRMS-EI (m/z): $[M]^+$ calcd for $C_{19}H_{17}N_2OPS$, 352.0799; found, 352.0804; HPLC (Daicel Chiralcel OJ, hexane/i-PrOH = 90:10, flow rate 0.5 mL/min) t_R 23.9 and 28.84 min.

4.4.20. *N*-[1-Cyano-1-(3-pyridyl)ethyl]diphenylphosphinic amide 25b

$[\alpha]_D^{23} = -2.4$ (c 1.05, CH_2Cl_2); ^{1}H NMR (400 MHz, $CDCl_3$, δ): 8.87 (d, J = 2.2 Hz, 1H), 8.51–8.49 (d, J = 4.7 Hz, 1H), 8.06 (d, J = 7.9 Hz, 1H), 7.95–7.90 (m, 2H), 7.79–7.74 (m, 2H), 7.54–7.39 (m, 7H), 7.29–7.27 (m, 1H), 4.23 (d, J = 7.4 Hz, 1H), 1.95 (s, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$, δ): 150.1, 146.9, 136.6 (d, J = 3.0 Hz), 133.6, 133.0, 132.6, 132.4 (d, J = 8.3 Hz), 132.2, 132.1, 131.8, 131.4, 131.3, 128.9, 128.7, 128.6, 123.5, 120.0 (d, J = 4.2 Hz), 54.9, 29.8 (d, J = 4.6 Hz); ^{31}P NMR (162 MHz, $CDCl_3$, δ): 21.2; IR (KBr): 3101, 2865, 2344, 1738, 1437, 1187, 996 cm^{-1}; MS m/z: 320 (M^+, 0.3), 216 (100), 199 (67), 140 (26), 124 (29), 77 (29); HRMS-EI (m/z): $[M]^+$ calcd for $C_{20}H_{18}N_3OP$, 347.1187; found, 347.1187; HPLC (Daicel Chiralcel OJ, hexane/i-PrOH = 90:10, flow rate 0.5 mL/min) t_R 22.9 and 25.7 min.

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